Modeling of Complex Coupled Fluid-Structure Interaction Systems in Arbitrary Water Depth

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Award: N00014-07-1-0008

LONG-TERM GOALS

The long-term goal of this research is to develop a robust multi-physics computational framework for the prediction and analysis of highly nonlinear dynamic behavior of naval systems in the marine environment of arbitrary water depth. The predictive capability will be sufficiently general for a variety of naval systems with a wide range of structural and mechanical complexities operating under deterministic and stochastic environmental conditions from deep water to the surf zone. Numerical models included in the framework will take into account nonlinear effects of free surface, turbulence, wave breaking, fluid-structure and structure-structure impacts, large geometry, material, and structural interaction with seabed sediments.

OBJECTIVES

In our previous research, we developed predictive capabilities to analysis highly nonlinear coupled fluid-structure interaction systems for deep water applications using relatively simple fluid and structural models. We analyzed the global deterministic and stochastic behaviors of these systems via perturbation theory, modern geometric analysis, stochastic differential equation approach, and path-integration solution techniques. This combination of analytical and numerical tools enabled us to gain a comprehensive understanding of the global behavior of the sensitive nonlinear coupled fluid-structure interaction systems. The analysis procedures developed are applicable to idealized systems with a few degrees of freedom, and not suitable to study the nonlinear behavior at the local level, which is the source that triggers the high sensitivity of the global system. The objectives of this phase of our research focuses on the development of predictive capabilities to study the detailed physics of coupled fluid-structure interaction at the local level and to expand the region of applicability of the computational framework to shallow water and the surf zone.

APPROACH

The approach to achieve the short term objectives is to perform an assessment on the existing predictive capabilities of the detailed physics from the perspective of naval applications; identify the gaps for needed further development; and to eliminate these gaps by developing advanced multi-physics models and corresponding solution techniques taking into account the details of coupled fluid-structure interaction and the effects of nonlinear free-surface and varying finite water depth. These

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Modeling of Complex Coupled Fluid-Structure Interaction Systems in Arbitrary Water Depth**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon State University,School of Civil and Construction Engineering,Coastal and Ocean Engineering Program,Corvallis,OR,97331-2302**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

models will be validated using laboratory experiments. They will then be used to explain the sources of the complex nonlinear sensitive response behavior predicted by the simpler multi-degree-of-freedom (MDOF) models developed earlier. Documentation of the findings of the global behavior, which is close to completion, has a focus on pinpointing the linkage between global and local behaviors.

The objectives will be achieved through the performance of the following tasks: (1) selection of appropriate analytical fluid and structural models suitable for marine systems for a selected range of ocean environmental conditions considered including shallow water and the surf zone; (2) decomposition of the multi-physics fluid-structure interaction domain into subdomains for efficient analysis and simulation; (3) development of needed multi-physics fluid-structure-interaction models and corresponding numerical codes; (4) development of coupling procedures connecting various subdomain boundaries; (5) identification of system parameters of the numerical models for selected naval systems; (6) performance of response analyses using the resulting numerical codes; (7) calibration of specific structural model response predictions with experimental results; and (8) extension of the analytical models and predictive techniques to stochastic cases.

WORK COMPLETED

The work completed in the past year falls into the following three areas: (1) advanced near-field fluid models and computational techniques development; (2) intermediate-field fluid model and fast computational technique development; and (3) evaluation of modeling of coupled fluid-structure interaction using existing capabilities.

Our research group has been working with the Livermore Software Technology Corporation (LSTC) since 2004 on the multi-physics code LS-DYNA. The main attractions of the existing code are its outstanding multi-material modeling features and multi-solution techniques for time domain simulation of highly nonlinear contact and contact/impact between fluid and solid in addition to solid and solid for automotive and other mechanical applications. We use the code as a computational platform and a unifying basis for further development in coupled fluid-structure-sediment interaction predictive capabilities pertaining to current and anticipated highly challenging naval application needs.

LS-DYNA modeling capabilities include multi-physics, multi-phase and multi-domain fluids and solids. It currently has finite-element (FE), boundary element (BE), element-free Galerkin (EFG) and smoothed particle hydrodynamics (SPH) numerical solution procedures for solving the governing dynamic equations in separate subdomains. We have studied selected portions of the large library of solution techniques and variety of existing features pertinent to naval systems modeling application needs. Selected subjects for improvement, including incompressible turbulence models, particle finite element technique for Reynolds-averaged Navier-Stokes (RANS) equations, and fast multipole algorithm for the nonlinear boundary-element technique are being developed by our research group. LS-DYNA currently has a compressible Navier-Stokes fluid model with an arbitrary-Lagrangian-Eulerian (ALE) formulation. In 2006, we developed a numerical solver for the RANS equations with a k-ε turbulence closure model in an ALE formulation (ALE-RANS). This past year, we implemented the model in a particle finite element method (PFEM) based framework for the ALE-RANS solver and submitted a journal paper recently [1]. In the paper, we presented the theory of ALE-RANS with a k-ε turbulence closure model and several numerical examples including: a pure CFD model with a backward facing step, a prescribed moving cylinder in a bounded domain, and a fluid-object interaction simulation of a bridge deck. Currently, we are developing a fluid-flexible structure interaction model without free surface using ALE-RANS and k-ε turbulence closure model implemented by PFEM. In this work a universal wall function (UWF) is introduced and implemented to more accurately predict the boundary layer flow on both fixed and moving walls including interfaces between the fluid and flexible structures [2]. The internal flow case has been validated with experimental results while the coupled fluid-structure interaction case is being calibrated with other numerical results available in the literature.

The LS-DYNA BE solution procedures had been mainly developed and used for solid modeling. The current BE solver does not have a fluid free-surface tracking capability or an efficient computational algorithm needed to handle complex large-scale 3-D simulations. To improve the BE modeling capabilities for intermediate fluid domain, we have been working on 3-D implementations of a collection of fully nonlinear potential flow (FNPF) codes to simulate the intermediate-field fluid domain. The collection (NWT3D) has originally been developed by a research group at URI with partial support from ONR. It contains a number of codes each with some of the state-of-the art features that our group has been looking for including boundary element method (BEM), fast multipole algorithm (FMA) and parallelization. A major feature of FMA is that can solve problems in the order of O(n) to O(nlogn), where n = number of nodes, unlike other codes that could solve only in $O(n^2)$ runtime. The collection of codes also has some wave generation capabilities including solitary waves, a directional flap wavemaker, an absorbing piston, and two impermeable walls on the side.

The NWT3D code was written mainly in FORTRAN and uses calls to an FMA library written in C. We have compiled the code and tested its runtime, which was found to progress linearly with the number of elements. The absorbing piston and absorbing pressure beach options are found to work fine and are complemented now by the incorporation of regridding option at user-specified time intervals. We have also completed the Piston wavemaker option for generation of solitary waves (motion is generated inside the code based on Goring's first order theory). More recently, we have implemented the Piston wavemaker motion using the external/user-specified input. We are working on the implementation of the multi-directional wavemaker operating on external input. These numerical wavemakers are critical for generating "input" waves to the fluid domain and facilitate validation of numerical models with known analytical and experimental results. These capabilities will enable us to simulate physical experiments at the 3-D wave basin at our wave basins.

We examined the current compressible flow fluid capability of LS-DYNA in modeling complex coupled fluid-structure interaction by applying it to simulate wave impact on a cylinder in the 3-D wave basin. We employed a local parallel cluster at Oregon State University and a couple of high-performance computer (HPC) clusters at Army Research Office (Aberdeen Proofing Ground) and performed a large number of large-scale numerical simulations and comparisons with wave-basin experimental results. We calibrated the numerical simulations with plane and focused waves on a single cylinder and a multiple cylinder array and compared the predicted and measured wave forces and overturning moments on the cylinders.

RESULTS

For 3-D analysis and simulation of deformable structures in shallow water and the surf zone, we developed the ALE-RANS theory with k-ε turbulence closure model (Fig.1) in 2006. In 2007, we implemented the ALE_RANS and k-ε turbulence closure model based on the particle finite element Method (PFEM) and obtained some satisfying results [1-2]. The numerical method has also been used to model the boundary layer effects to turbulent flow [3]. Currently, we are validating the code using classical CFD benchmark models [4] to examine the stability and convergence performance. It is found that our PFEM code with turbulence model matches the experimental data well. We developed several boundary conditions including no-slip and free-slip to handle various boundary layer problems. We are implementing a universal wall function to take into account more complex boundary layer problems for both fixed and moving walls. These capabilities are essential to model the interface between solid and fluid in fluid-structure interaction applications. The universal wall function capability will make our code more general and mesh-independent, which will not require the users to predetermine the behavior of the fluid at the boundary and specify the mesh size at the boundary for mesh generation.

Figure 2 illustrates the dimension and boundary conditions of the computational domain for the model of backward facing step. Figures 3(a)-(c) show the velocity magnitude contour, pressure contour and the contour of the normal nodal distance to the wall (obtained from the fast marching method [5]), respectively. The recirculation and the reattachment of the shear flow to the wall can be clearly observed in Figure 4. Figures 5 and 6 show a comparison of the normalized horizontal velocity profile and turbulence intensity against the experimental data of Denham et al [4]. The reattachment length from this simulation is about 6H, which matches the experimental value in [2] well. Figure 7 illustrates the geometry and boundary condition of a flow passing an oscillating cylinder with a prescribed motion. The *Reynolds number* under consideration in this case is 4000. The cylinder is given a rigid-body motion of $u(t) = 2\pi fd \cos(2\pi ft)$ in the vertical direction at a frequency $f = 0.1\,Hz$ and an amplitude of $d = 2.0\,m$. Figure 8 demonstrates the mesh movements of the ALE formulation as the cylinder oscillates through a range of typical positions in the fluid domain within one cycle. Figures 9-11 show the contours of velocity magnitude, turbulent kinetic energy k and turbulent dissipation rate ε as the cylinder moves through different positions.

Finally, the capability of the ALE-RANS model for coupled fluid-object interaction is demonstrated here with an example of an H-profile bridge section restrained by a rotational spring and a vertical translational linear elastic spring (Figure 12). The bridge section is assumed rigid with horizontal constraint and only rotational/translational motion is considered. The rigid object is exposed to a uniform flow at the inlet in the horizontal direction. The elastic restraints of the supports represent the torsional stiffness and the vertical stiffness of a simplified suspension bridge section, respectively. The details of the mesh around the bridge deck are shown in Figure 13. Figure 14 shows that after roughly 70s, the bridge deck starts to resonate with large amplitude induced by the vortex shedding. Comparing the ALE-RANS solution to the ALE-NSE solution in Figure 14, we found that the turbulence effects to the amplitude of the vertical translational displacements are negligible, but the turbulence effects to the rotational displacements are dominant. Due to the turbulence influence, the rotational angle from ALE-RANS solution is larger than the rotational angle from ALE-NSE solution. Thus, this example shows that for moderate Reynolds number flow, the turbulence effects are important and should be taken into account for more accurate prediction. Figures 15-17 show the contours of velocity magnitude, turbulent kinetic energy k and turbulent dissipation rate ε as the cylinder moves through different positions.

For NWT3D development, Figure 18 illustrates the performance of NWT3D code with increase in number of elements. It can be observed that the run time is linear with model size. A very fine model of the 3-D wave basin at Oregon State University with dimensions of 43.630 x 26.520 x 0.75 (m) was prepared using boundary elements of 200 x 100 x 10 in X, Y, Z directions. The model has a total number of nodes of 47,246 and number of elements of 46,000. Considering that the BEM used in the code requires only surface mesh, there were considerable savings in mesh size. The equivalent traditional FEM solid mesh would require 200,000 elements. The model was run for 30 time steps (final time being 0.79 sec) using solitary wave (Tanaka's) on a single CPU. It took about 13.5 hours of runtime.

IMPACT/APPLICATIONS

The advanced, state-of-the-art fluid-structure-interaction models including breaking waves adopted in this project, when fully developed, will enhance the modeling, prediction, operation and control capabilities of naval marine systems over a wide range of environmental conditions including the littoral zone, where rapid deployment of floating platforms and mine counter measures is essential. The 3-D numerical code being developed will provide additional tools to validate the accuracy of estimation of extreme value and cumulative fatigue predictions of complex responses of highly nonlinear marine structural systems and will advance the development of a systematic analysis procedure.

TRANSITIONS

Several analytical and numerical techniques developed in this research project have been used in other naval structural system analyses. Specifically, NFESC has employed the probability- and time-domain stochastic techniques to analyze nonlinear stability and capsizing probability of barges. We are currently developing 3-D fully-coupled analysis and simulation capabilities for mine scour problem using the LS-DYNA numerical code.

RELATED PROJECTS

This research project complements those supported by other ONR programs on the study of physical systems including nonlinear ocean waves and manned and unmanned structures. There are significant cross fertilization of ideas and development/implementation of numerical techniques on nonlinear stochastic analyses between this project and those under hydrodynamics, mathematical sciences, physics and other programs. This research will eventually benefit higher category programs when the resulting systematic analysis methodology can be employed in the analysis of rogue waves; the design of Naval ships, barges, platforms and other special "structures" including remotely operated vehicles for mine detection and sweeping; and mine scour.

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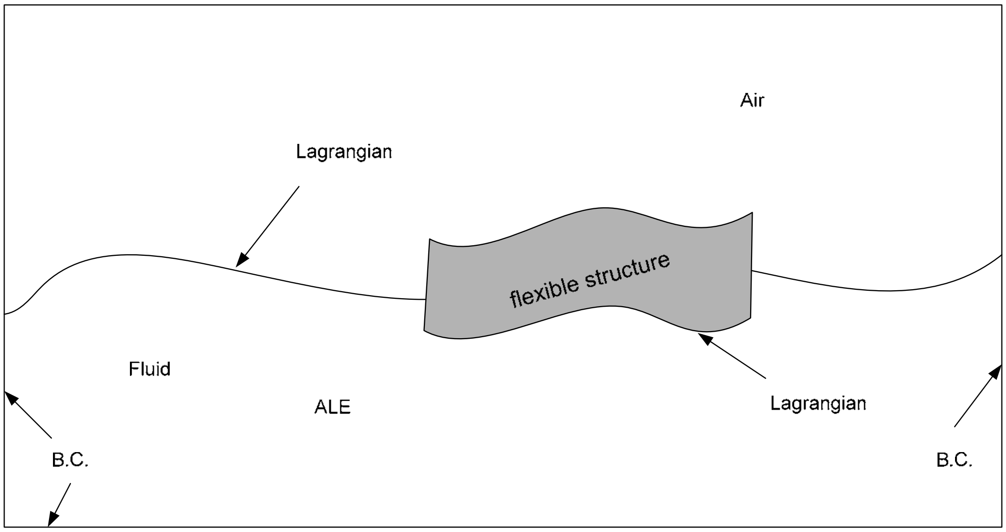


Figure 1. Mathematical model for FSI problem

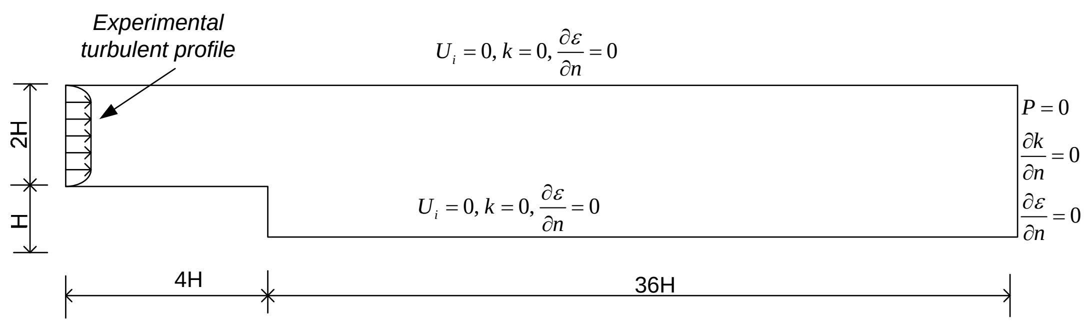
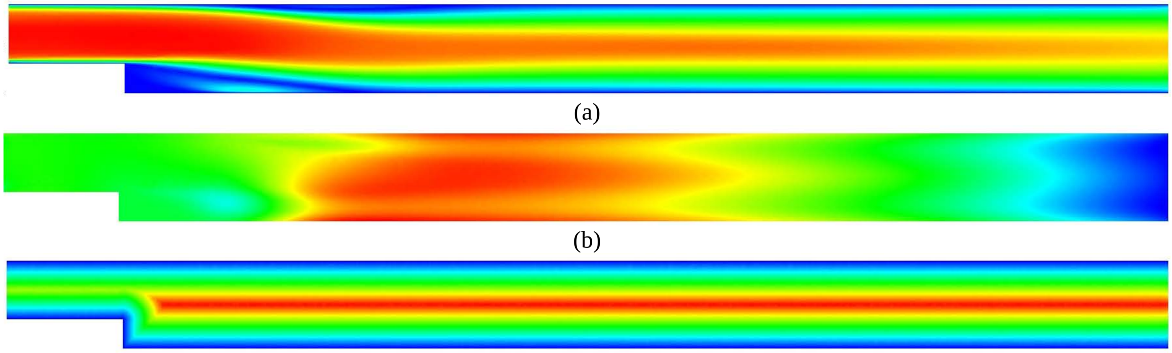


Figure 2. Geometry, dimensions and boundary conditions of the computational domain



(a)

(b)

(c)

Figure 3 Incompressible flow past a backward facing step. (a) Velocity magnitude contour; (b) Pressure contour; (c) The contour of the normal nodal distance to the wall.

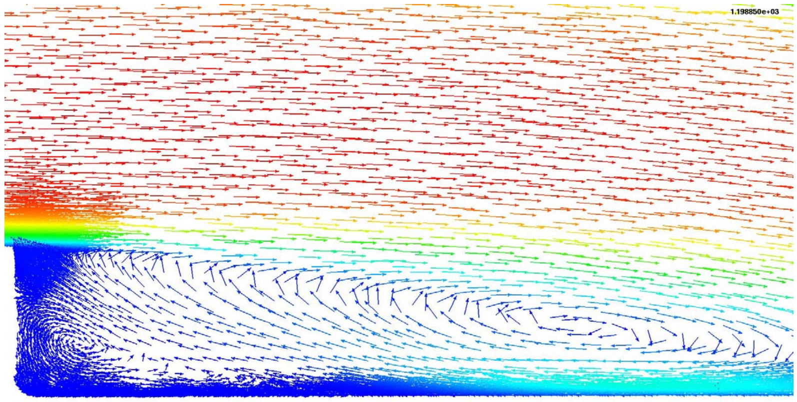


Figure 4. Velocity vector field of the left corner at t=1198.85 sec

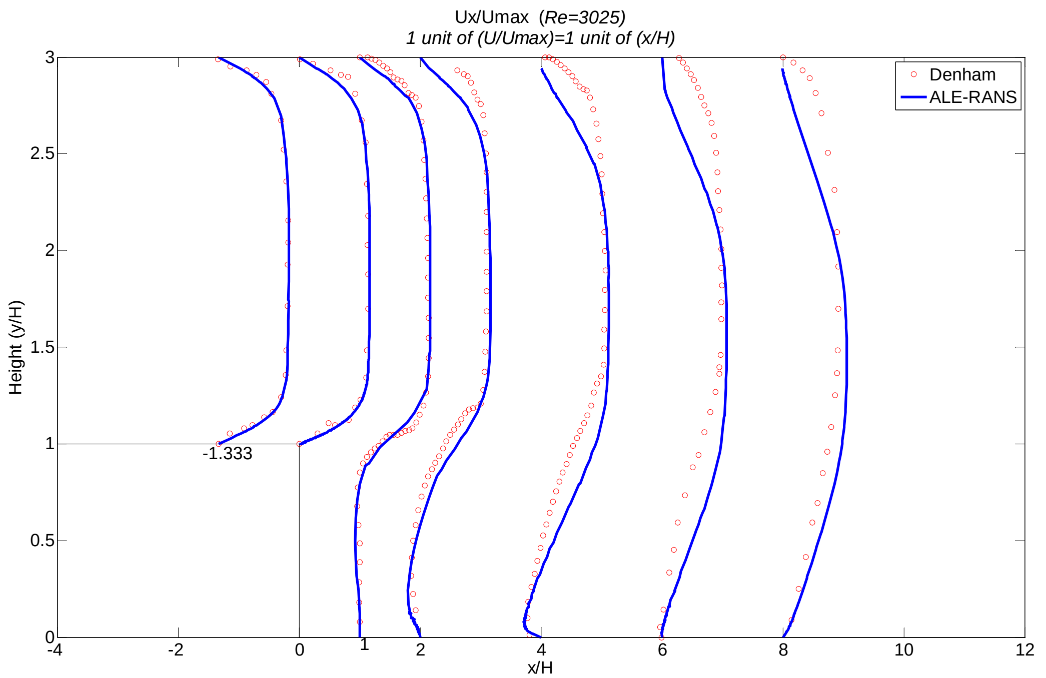


Figure 5. Normalized velocity profile at different downstream sections (Re=3025)

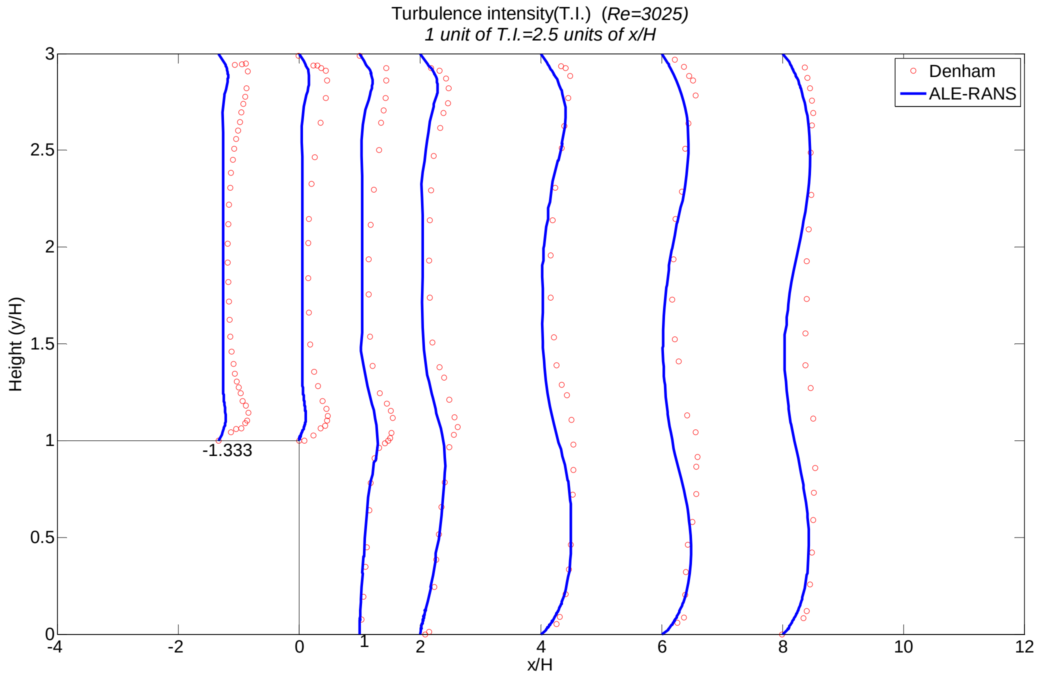


Figure 6. Turbulence intensity at different downstream sections (Re=3025)

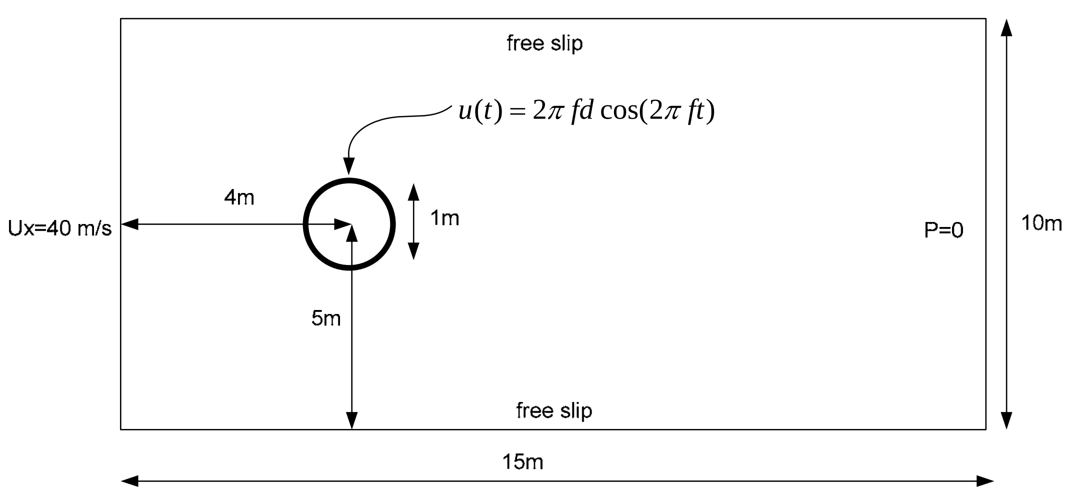
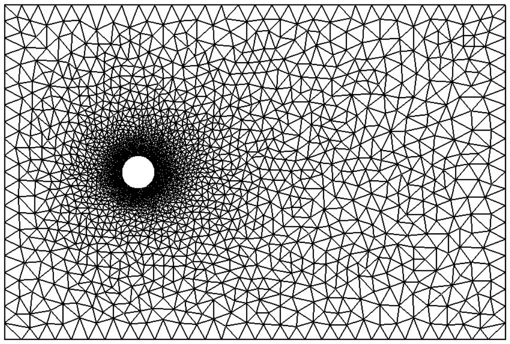
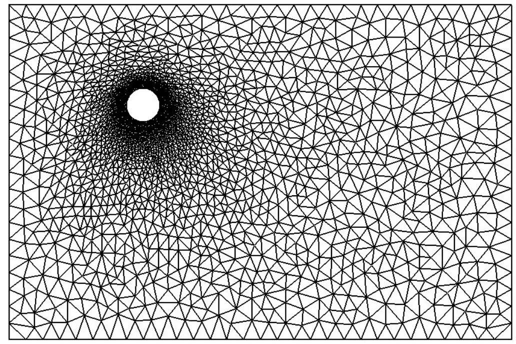
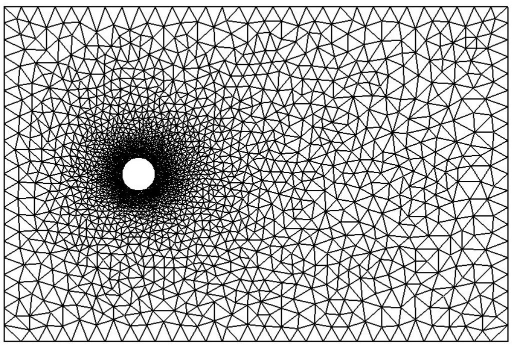
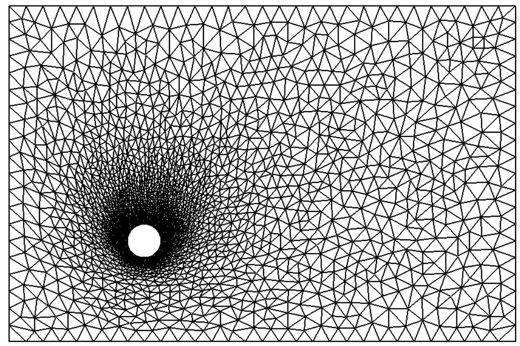


Figure 7. Flow past an oscillating cylinder

(a) t=89.9 sec (b) t=92.4 sec

(c) t=94.9 sec (d) t=97.4 sec

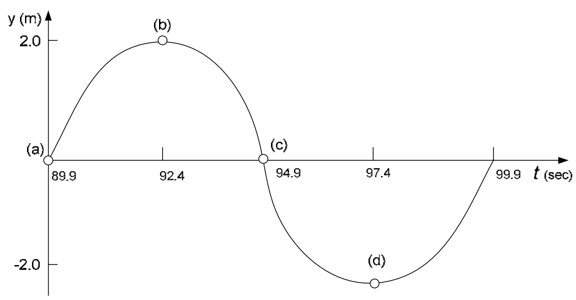
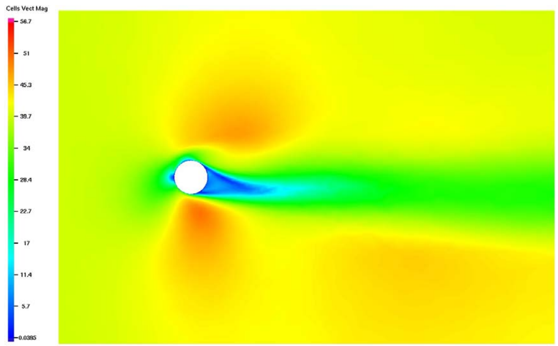
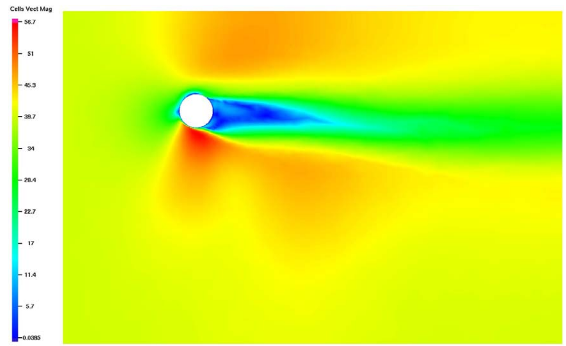


Figure 8. Mesh movements in one oscillating cycle for the ALE algorithm



(a) t=89.9 sec



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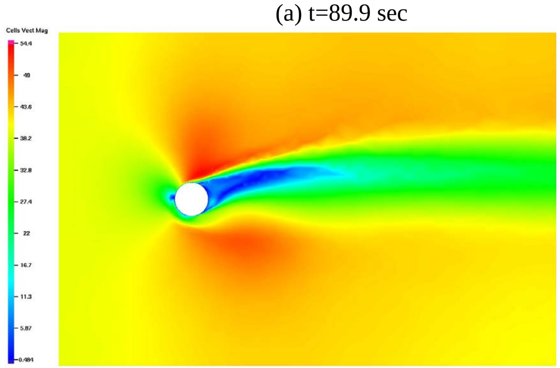

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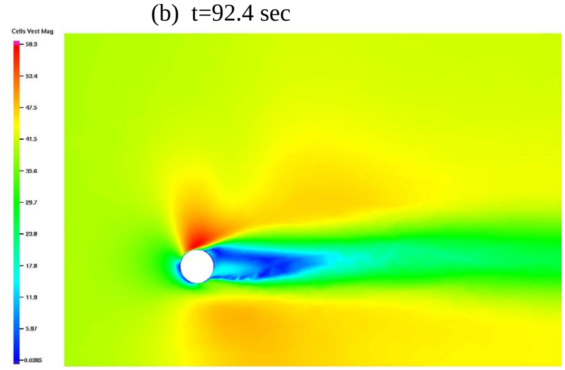
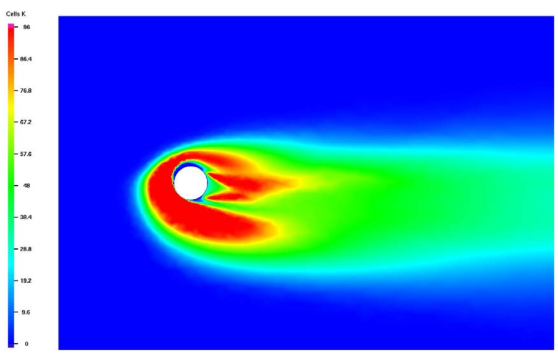
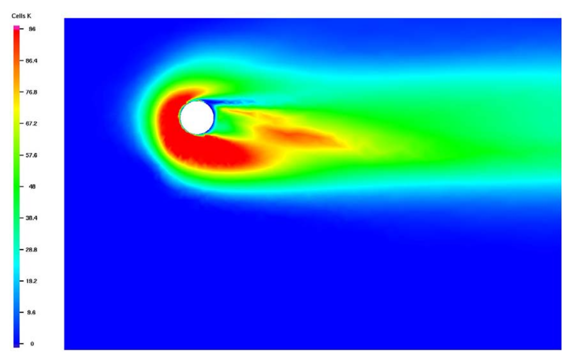


(d) t=97.4 sec

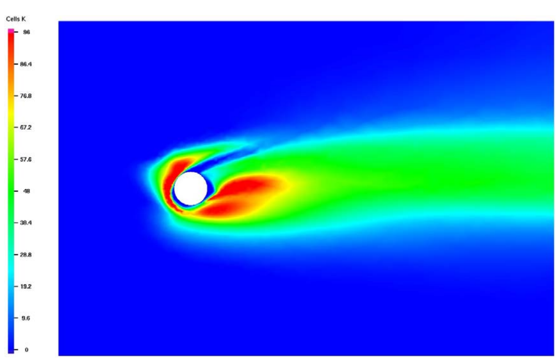
Figure 9. Contour of velocity magnitude when cylinder oscillates in the fluid



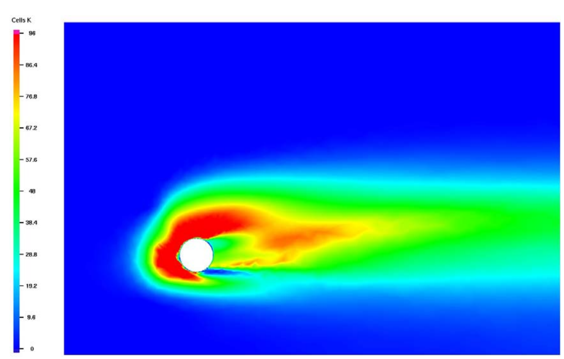
(a) t=89.9 sec



(b) t=92.4 sec

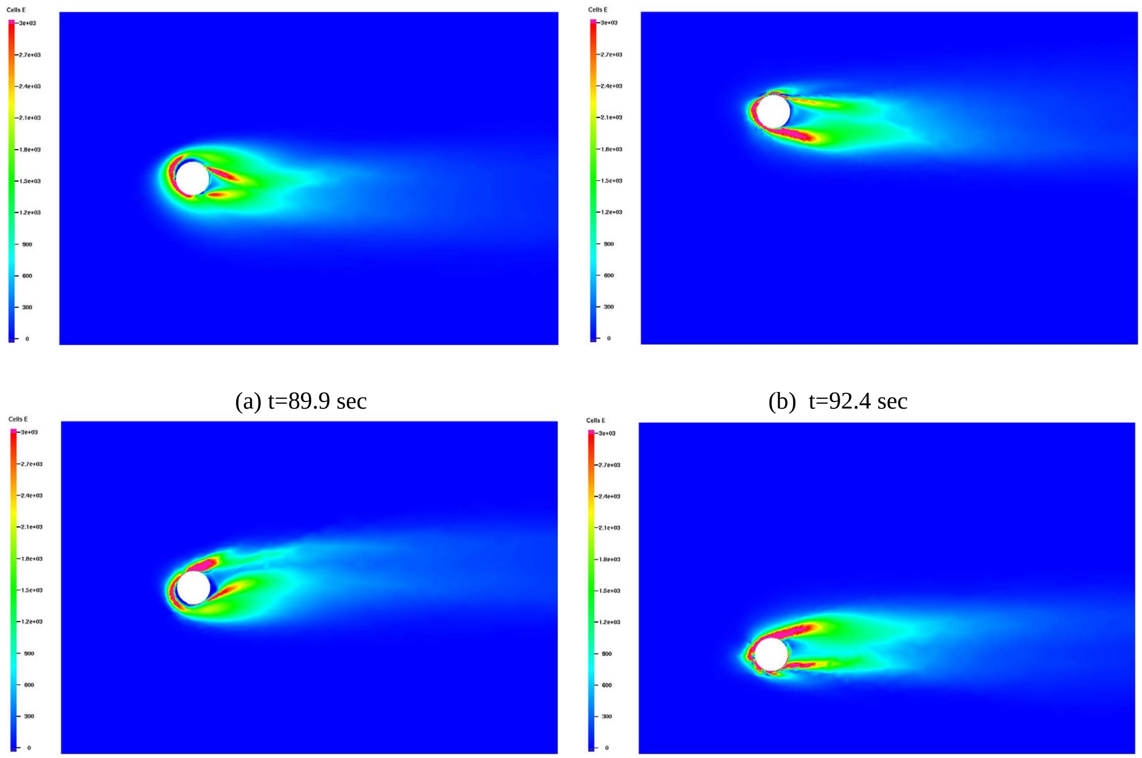


(c) t=94.9 sec



(d) t=97.4 sec

Figure 10. Contour of turbulent kinetic energy k ***when cylinder oscillates in the fluid***



(a) t=89.9 sec (b) t=92.4 sec

(c) t=94.9 sec (d) t=97.4 sec

Figure 11. Contour of turbulent dissipation rate ε when cylinder oscillates in the fluid

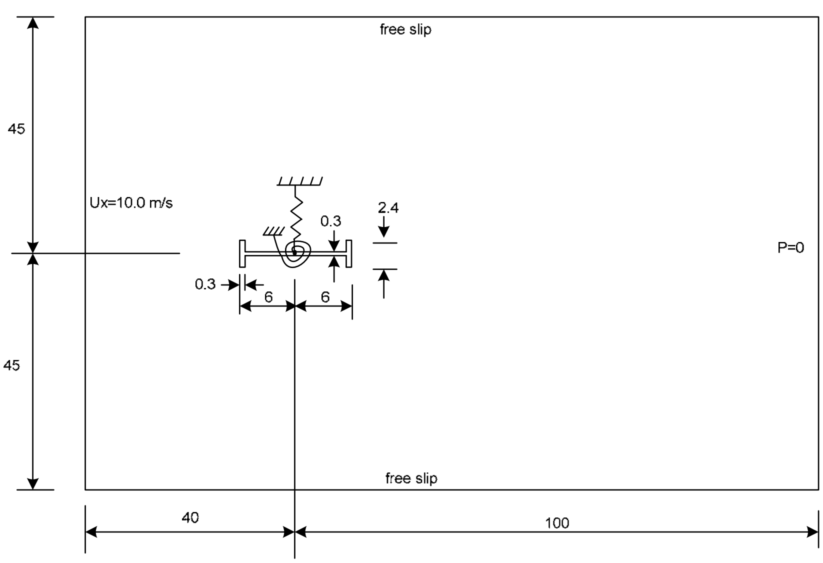


Figure 12. Flutter of bridge deck, geometry ([m]) and boundary conditions of the problem

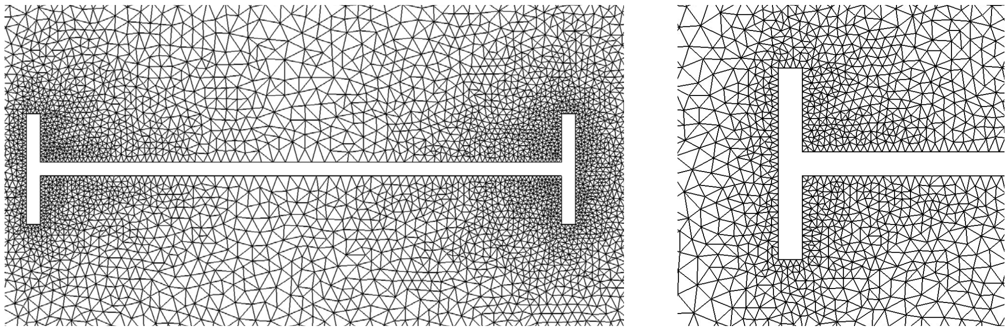


Figure 13. Mesh around the bridge deck

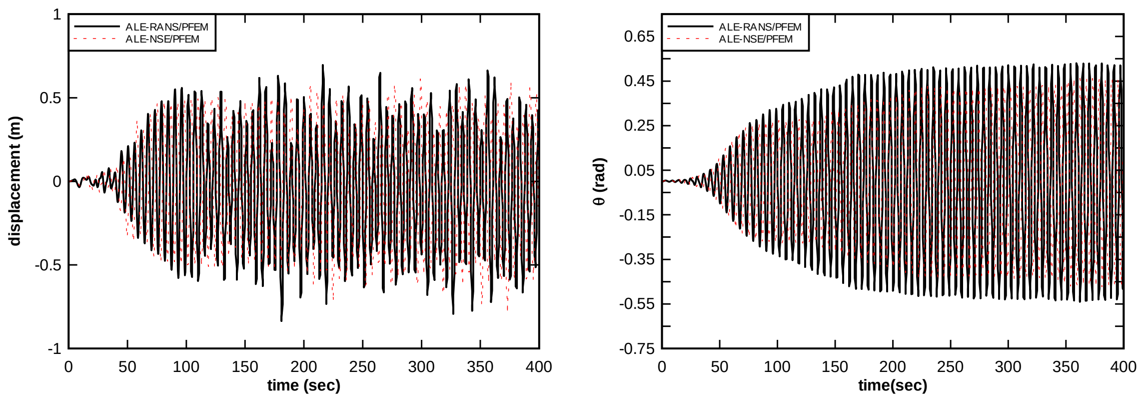


Figure 14. Flutter of the bridge deck, time history of translational and rotational movements; $\Delta t = 0.05s$

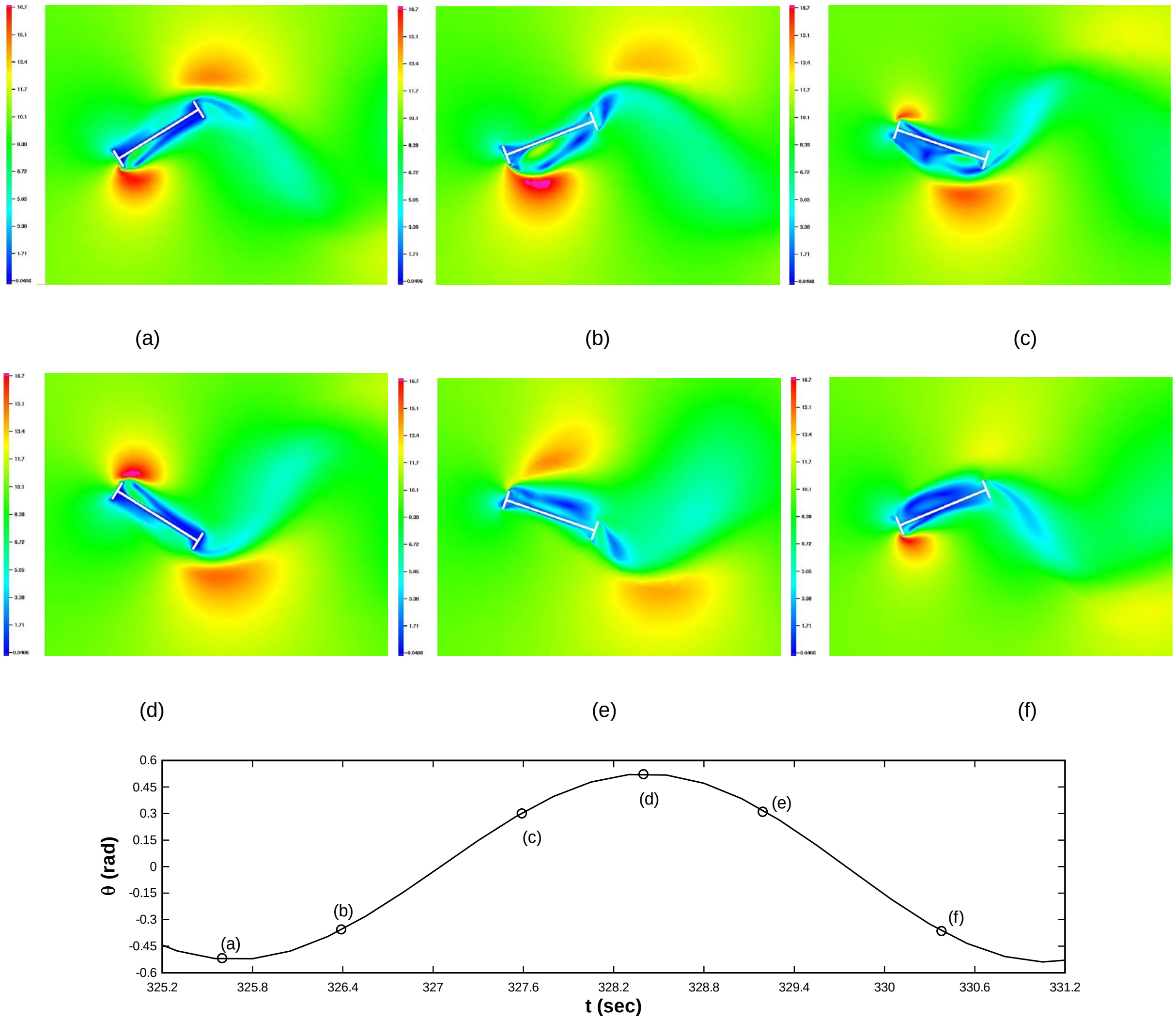


Figure 15. Flutter of the bridge deck, distribution of velocity magnitude at six typical positions

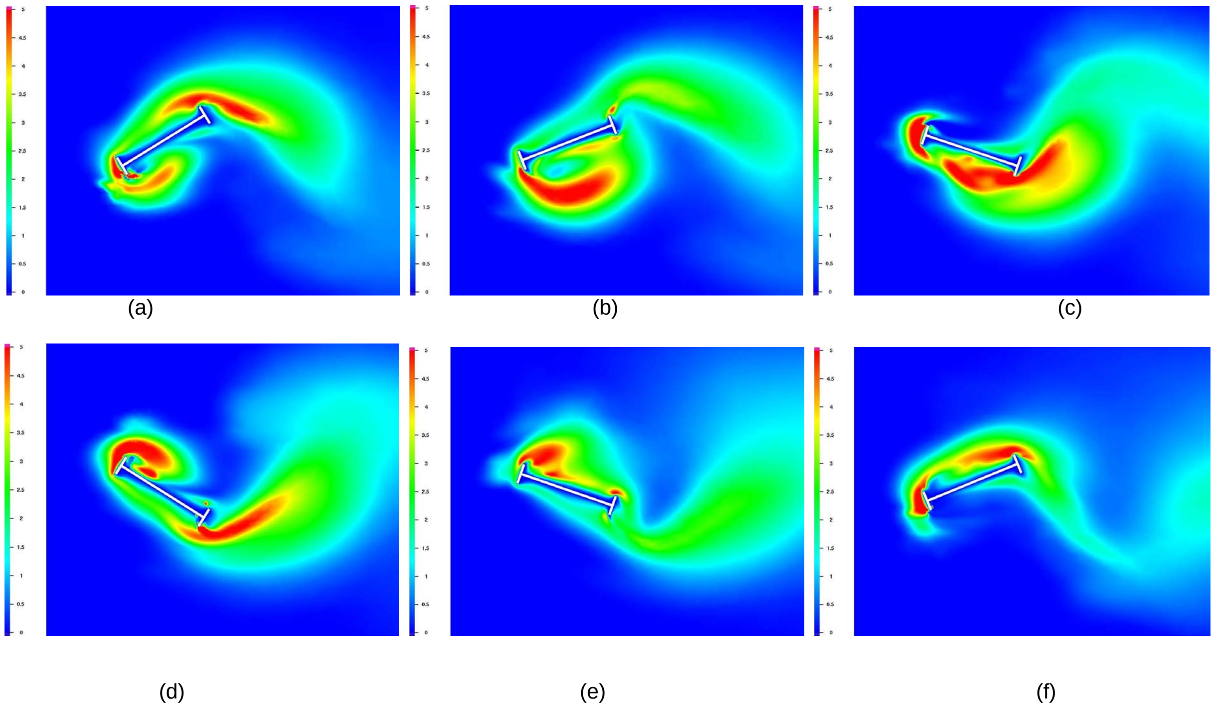


Figure 16. Flutter of the bridge deck, distribution of turbulent kinetic energy k at six typical positions

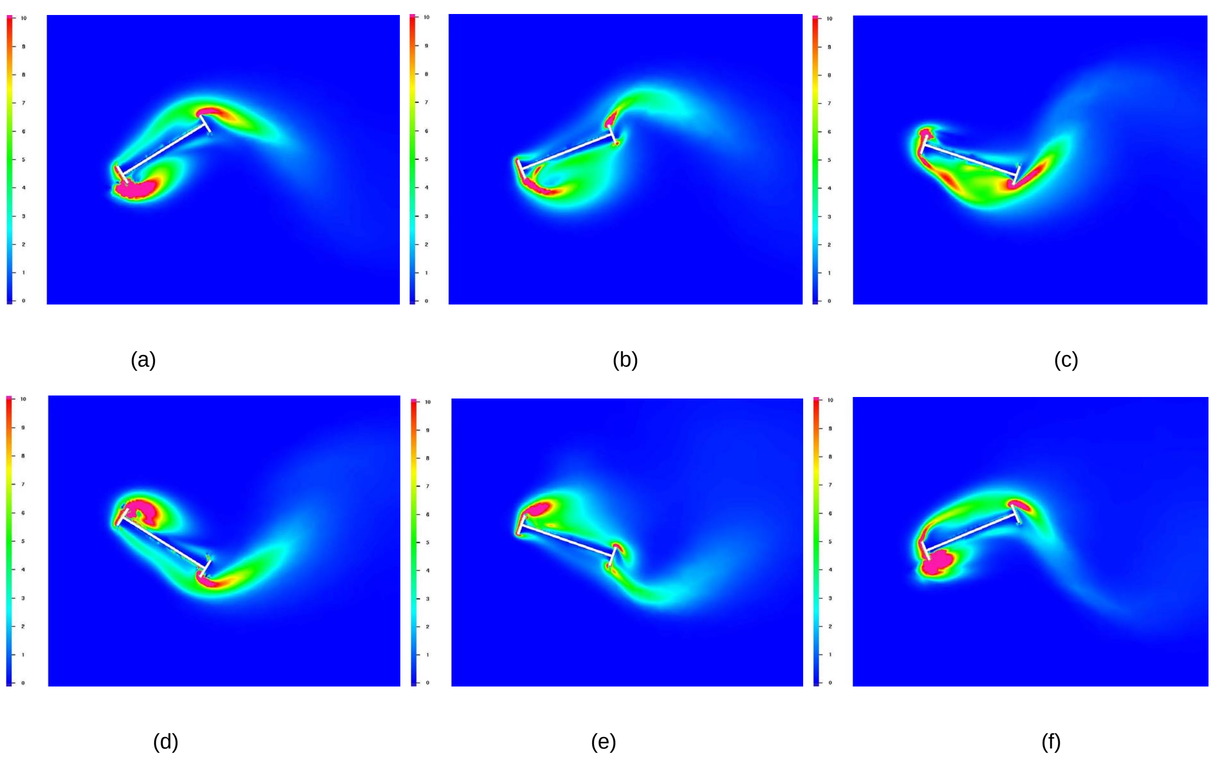


Figure 17. Flutter of the bridge deck, distribution of turbulent dissipation rate ε at six typical positions

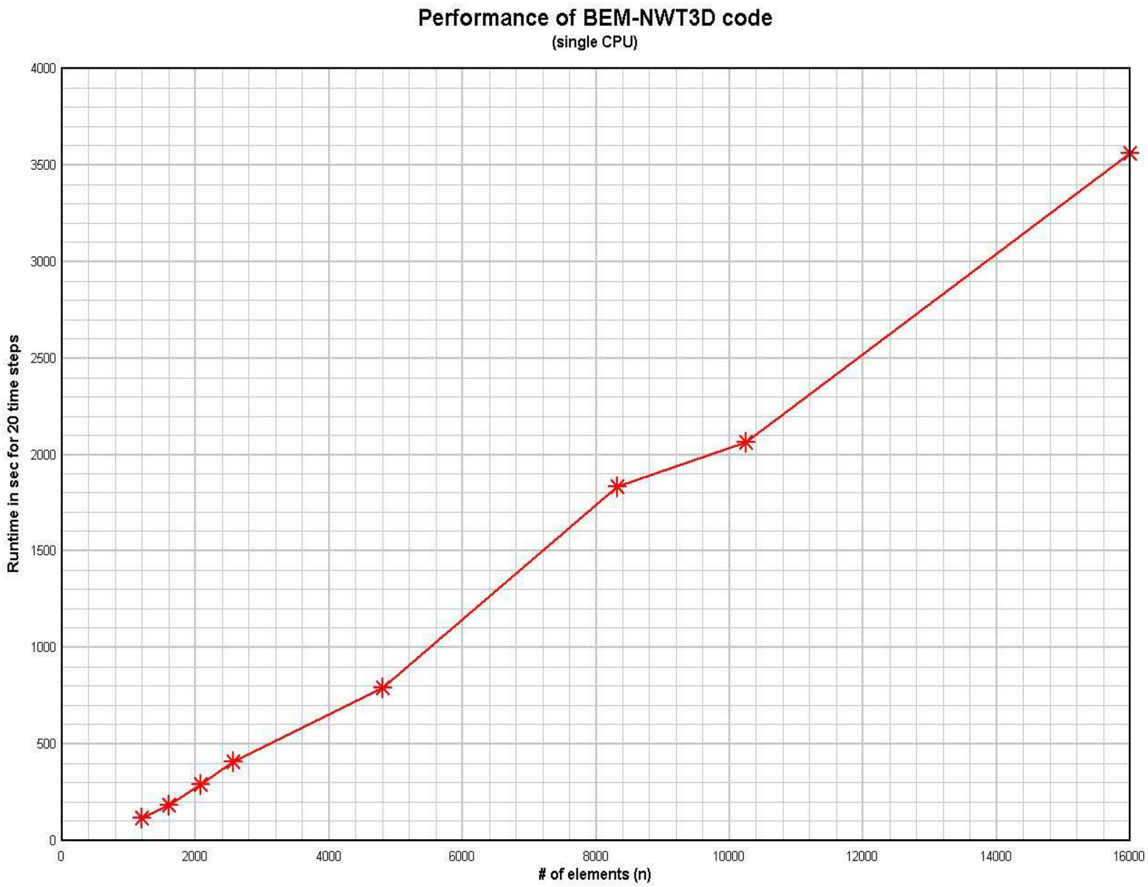


Figure 18 Performance of NWT3D code with increase in number of elements

PUBLICATIONS

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